Ecological Indicators 87 (2018) 196–208

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Changeability of reliability, resilience and vulnerability indicators with respect to drought patterns

Zeinab Hazbavi[a], Jantiene E.M. Baartman[b], João P. Nunes[b,c], Saskia D. Keesstra[b], Seyed Hamidreza Sadeghi[a,*]

[a] Department of Watershed Management Engineering, Faculty of Natural Resources, Tarbiat Modares University, Iran
[b] Soil Physics and Land Management Group, Wageningen University and Research, Netherlands
[c] CE3C – Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciências, Universidade de Lisboa, Portugal

ARTICLE INFO

Keywords:
Adaptive strategy
Conceptual framework
Environmental indicators
Health assessment
Watershed planning

ABSTRACT

Climate-related extremes such as droughts have led to significant impacts on some watersheds. To assess watershed health and develop effective management plans, information about the function and structure of the watersheds in the context of their climatic response, especially to take into account rainfall anomalies and climate change adaptation, is needed. Integration of climatic variables with reliability, resilience and vulnerability (RRV) indicators, is a novel approach for generating this information. This study investigated the behavior of RRV indicators with respect to rainfall variability and drought patterns for three watersheds governed by different climates. Reliability was defined as the probability of a watershed to be in the range of satisfactory Standardized Precipitation Index (SPI) values. Resilience was indicated as the speed of recovery from an unsatisfactory condition. Vulnerability was defined as a function of the exposure of a watershed to climate change and variation using the SPI. The study areas were the Foyle Watershed in Northern Ireland (temperate oceanic, Cfb), the Xarrama Watershed in Portugal (Mediterranean hot summer, Csa) and the Shazand Watershed in Iran (moderate to cold semi-arid (Bsk). Based on the SPI pattern of each watershed, the SPI of −0.1 for the Foyle and Xarrama watersheds and +0.1 for the Shazand Watershed was selected as the drought threshold. The drought based RRV index was subsequently calculated from long-term (1981–2012) RRV indicators, resulting in means of 0.52 ± 0.25, 0.53 ± 0.21 and 0.30 ± 0.18 for the three watersheds, respectively. These means reflect the status of the watersheds in terms of climatic conditions, which was moderate dry (0.41–0.60) for the Foyle and Xarrama watersheds and dry (0.21–0.40) for the Shazand Watershed. The temporal trend of the drought based RRV index was found to be non-significantly increasing (P-value > 0.52) for the Foyle and Xarrama watersheds and non-significantly decreasing for the Shazand Watershed (P-value > 0.48). The vulnerability indicator and drought based RRV index were significantly (p-value = 0.00) affected by the climatological gradient. The results of the conceptual framework linked to statistical trends can provide researchers, policy makers, and land managers a more comprehensive base to assess variability of watershed health and design drought management plans.

1. Introduction

Recent changes in climate have widespread impacts on human and natural systems (IPCC, 2014). Among other things, climate change has the potential to disrupt and modify hydrological regimes and thus affect watershed conditions and associated management approaches (Sood and Ritter, 2011; IPCC, 2014; Teegavarapu, 2017; Zareian et al., 2017; Herath and Hasanov, 2017). Increases in the frequency or intensity of ecosystem changes such as droughts have been detected in many parts of the world and are, in some cases, attributed to climate change (IPCC, 2014).

Droughts are considered to be one of the world's costliest natural disasters affecting a variety of sectors (Esfahanian et al., 2017) and rainfall, or lack thereof, is a factor in their occurrence. Climate change has been recognized to impact rainfall patterns in various low to medium latitude mid-continental regions and in already arid areas in around the world (McMichael et al., 2003). Hence, quantifying rainfall patterns and variability has been an area of increasing interest for many

* Corresponding author.
E-mail addresses: z.hazbavi@modares.ac.ir (Z. Hazbavi), jantiene.baartman@wur.nl (J.E.M. Baartman), jpcn@ua.pt (J.P. Nunes), saskia.keesstra@wur.nl (S.D. Keesstra), sadeghi@modares.ac.ir (S.H. Sadeghi).

https://doi.org/10.1016/j.ecolind.2017.12.054
Received 28 August 2017; Received in revised form 25 November 2017; Accepted 22 December 2017
Available online 04 January 2018
1470-160X/ © 2017 Elsevier Ltd. All rights reserved.

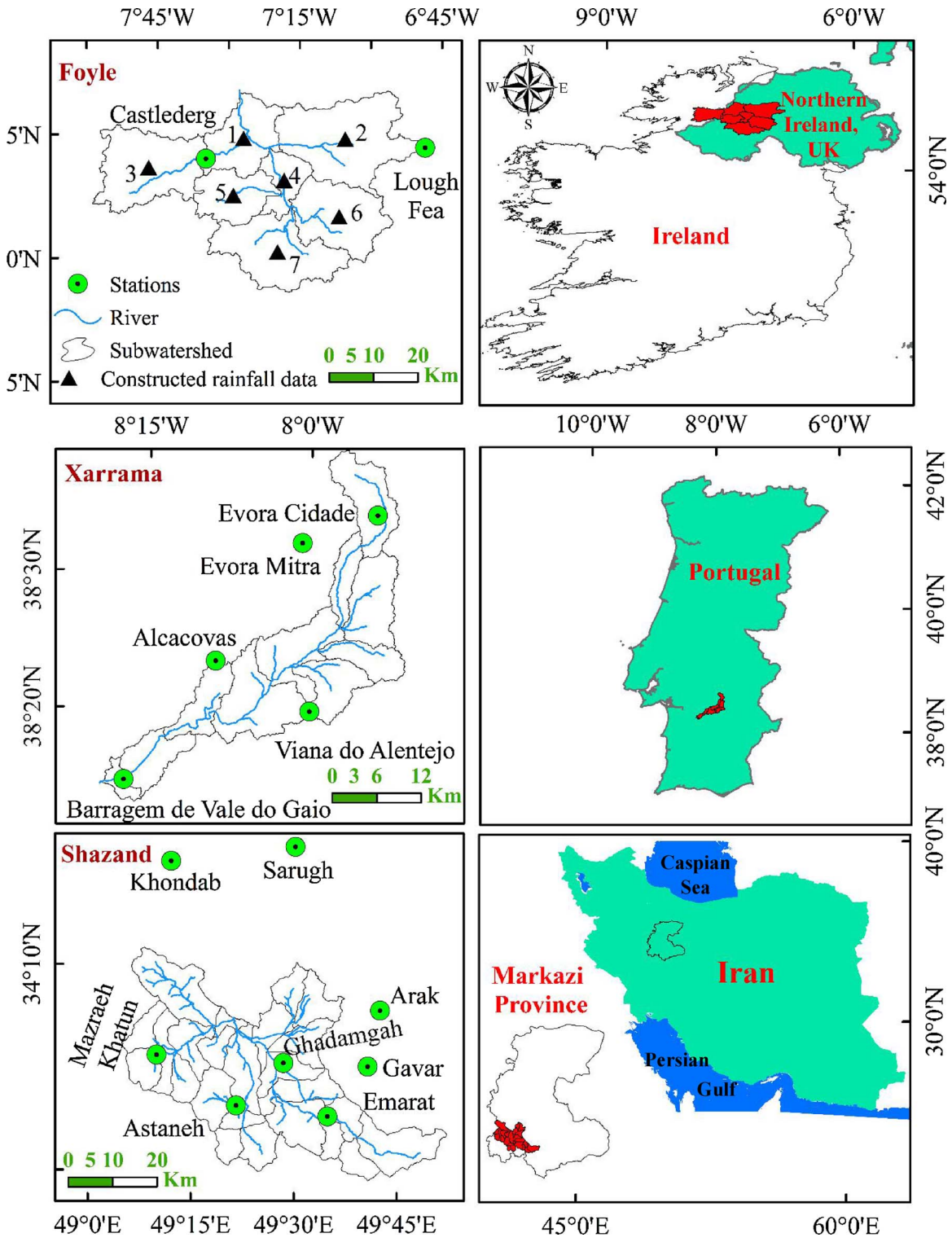

Fig. 1. General view and main characteristics of study watersheds.

researchers studying droughts. Additionally, adaptation to future severe droughts requires insight into the drivers of the drought and its possible impacts (van Dijk et al., 2013).

The reliability-resilience-vulnerability framework (RRV) was initially elaborated by Hashimoto et al. (1982) to describe the performance of a multipurpose reservoir system. Each complement criterion (i.e., reliability, resilience and vulnerability) assesses different aspects of the watershed system. Reliability measures the frequency or probability of the watershed being in a satisfactory state during the total data period. Resilience measures how quickly, on average, a system rebounds to a satisfactory state after reaching an unsatisfactory state. It accounts for the number of rebounds as a percentage of total unsatisfactory study time. Vulnerability assesses how severe the unsatisfactory state is or the factors that caused it. Assessing these metrics (Asefa et al., 2014) provides insight into system performance in changing or varying climatic conditions. The ability of RRV analysis to distinguish trends using long term data is well documented for water resources systems (Hashimoto et al., 1982; Maier et al., 2001; Kjeldsen

and Rosbjer, 2004; Jain and Bhunya, 2008; Jain, 2010).

Despite the existence of many theories and methodologies for characterizing drought in watersheds, the concept of measuring watershed performance using RRV indicators has only recently emerged (Maity et al., 2013; Chanda et al., 2014; Sadeghi and Hazbavi, 2017) and has not (yet) been considered widely. Together, RRV indicators provide a comprehensive approach to analyze the probability of success or failure of a watershed and the rate of its recovery from unsatisfactory states, as well as quantifying the expected consequence of being in unsatisfactory states for extended periods. Assessing these comprehensive indicators over the long term provides insight into watershed performance under changing or varying climatic conditions (Asefa et al., 2014).

There are many indices used for the evaluation of climate variability. The Standardized Precipitation Index (SPI) is a precipitation deficit or surplus indicator for assessing climatic variability (Khan et al., 2008) and a probabilistic means of characterizing rainfall anomalies (Keyantash and Dracup, 2002). The SPI has been used as a measure of the deviation in precipitation from average conditions over time (Jenkins, 2012; Freire-González et al., 2017). The SPI developed by McKee et al. (1993) is applicable for both agricultural and hydrological purposes (Edwards and McKee, 1997) and has been applied to define and monitor the status of droughts (Shahabfar and Eitzinger, 2013; Hosseinizadeh et al., 2015). It is being used as a widely accepted and a universal meteorological drought index which allows comparisons of drought conditions across different climate regions (Chen et al., 2009; Mostafazadeh and Zabihi, 2016). The SPI can be determined for different time periods. Short time scales of one to four months can be used as an indicator of surface runoff and soil moisture drought (Loukas and Vasiliades, 2005), and longer time frames can reflect the dynamics of different types of droughts (i.e., agricultural, hydrological, and meteorological droughts).

The RRV framework has been used in different fields including hydrology, ecology and recently watershed sustainability and health (e.g., Hashimoto et al., 1982; Naeem, 1998; Mondal et al., 2009; Sood and Ritter, 2011; Hoque et al., 2012; Asefa et al., 2014; Hoque et al., 2016; Hazbavi and Sadeghi, 2017). However, no comprehensive study has been conducted to check the sensitivity of the RRV framework based on SPI variability as an indicator of drought in different climates. The present study was designed to (1) customize the RRV framework for the important climatic criterion of SPI in three watersheds with varying climates; (2) interpret the behavior of the RRV indicators with respect to the rainfall anomaly; and (3) analyze the temporal trend of the rainfall, SPI, and RRV indicators and SPI based RRV index values for the three watersheds over the time period of 1981–2012.

2. Materials and methods

2.1. Description of study watersheds

Three watersheds, viz. Foyle (Ireland), Xarrama (Portugal) and Shazand (Iran), were selected and subjected to RRV analyses. The three study watersheds representing variety of climatic gradients from temperate to Mediterranean and semiarid (OSI, 2010; Hazbavi and Sadeghi, 2017; Nunes et al., 2017) were selected by virtue of accessibility to basic high resolution data, which were essentially required for the RRV framework modeling. A general view and characterization of the study watersheds are shown in Fig. 1.

2.1.1. Irish Watershed – Foyle

The Foyle Watershed (1863 km^2) is located in Northern Ireland, UK, at about 154 m above mean sea level and has a temperate oceanic climate (Cfb) (OSI, 2010). Annual rainfall exceeds 2000 mm in the upland regions, while the low lying areas receive approximately 1000 mm per year (www.nwirbd.com). The mean annual temperature within the watershed was 8.5 °C during the period 1981–2012. Land-use in the watershed comprises mainly intensive and natural pastures, scrublands, and peat bogs.

2.1.2. Portuguese Watershed – Xarrama

The Xarrama Watershed (528 km^2) is located in southern Portugal at about 200 m above mean sea level. The rainfall regime in Portugal is highly seasonal, typical for a Mediterranean hot summer climate (Csa) with a rainy season in the autumn and winter (November to March) and an extremely dry summer (Mourato et al., 2010). River flows are very irregular, with severe droughts contrasted with high flood discharges (Ramos and Reis, 2002; da Silva et al., 2015; Nunes et al., 2017). The mean annual temperature of the watershed was 16.0 °C between 1981 and 2012. Land-use is mainly agro-forestry consisting of pasture and evergreen oaks. The Xarrama River supplies water for the Alto Sado irrigation network, a system susceptible to recurrent droughts and under expansion as an adaptation measure to climate change (Nunes et al., 2017).

2.1.3. Iranian Watershed – Shazand

The Shazand Watershed (1739 km^2) is located in the Ghareh-Chaie Basin in southwest of Markazi Province, Iran at approximately 2170 m above mean sea level. This watershed has a semi-arid climate (Bsk) with hot summers and cold winters. The mean annual temperature of the watershed based on neighboring Arak Station was 13.7 °C during the period 1981–2012. The Shazand plain has a fertile soil, which enables agricultural activities. In addition, the watershed has been under rapid industrialization which has resulted in changing hydrological behavior. Between 1988 and 2000 there was considerable development of cities and industries and extension of irrigation and orchard fields (Mokhtari et al., 2011; Darabi et al., 2014; Davudirad et al., 2016; Hazbavi and Sadeghi, 2017).

2.2. Methodology

The temporal drought pattern was characterized by integrating the SPI with the RRV framework for the three watersheds. Fig. 2 gives an overview of the study methodology.

2.2.1. Rainfall data records

The monthly rainfall data for a 32 year-period (October 1981-September 2012), collected from as many rainfall recording stations as possible, were used to characterize the drought based RRV framework. This is in line with the World Meteorological Organization (WMO) and Intergovernmental Panel on Climate Change (IPCC) recommendations of a minimum study period of 30 years (García-Garizábal et al., 2014; IPCC, 2014). In the Foyle Watershed, the existing rain gauge network was deemed insufficient to capture the large topographically-induced rainfall variability (Fig. 1). Therefore, the rainfall data was corrected using a topographic lapse rate method (following Galván et al., 2014). For this purpose, a relationship was developed between rainfall and altitude from regional stations, and a virtual precipitation station was consequently added to the centroid (geometric center) of each sub-watershed and corresponding precipitations were estimated.

To provide more insight into the rainfall and SPI variability in the subject watersheds, the monthly data were also aggregated and long-term annual means were produced for each of the study stations. In addition, the Thiessen method (Sadeghi and Hazbavi, 2017) was used to generate spatial rainfall means for the study areas based on the geographical distribution of the climatic stations. The main characteristics of the stations and constructed points for the watersheds are summarized in Table 1.

2.2.2. Calculation of the standardized precipitation index (SPI)

The 1-month SPI was computed with monthly rainfall as primary input (Owrangi et al., 2011) by fitting a gamma distribution to the frequency distribution of the data. Each probability density function

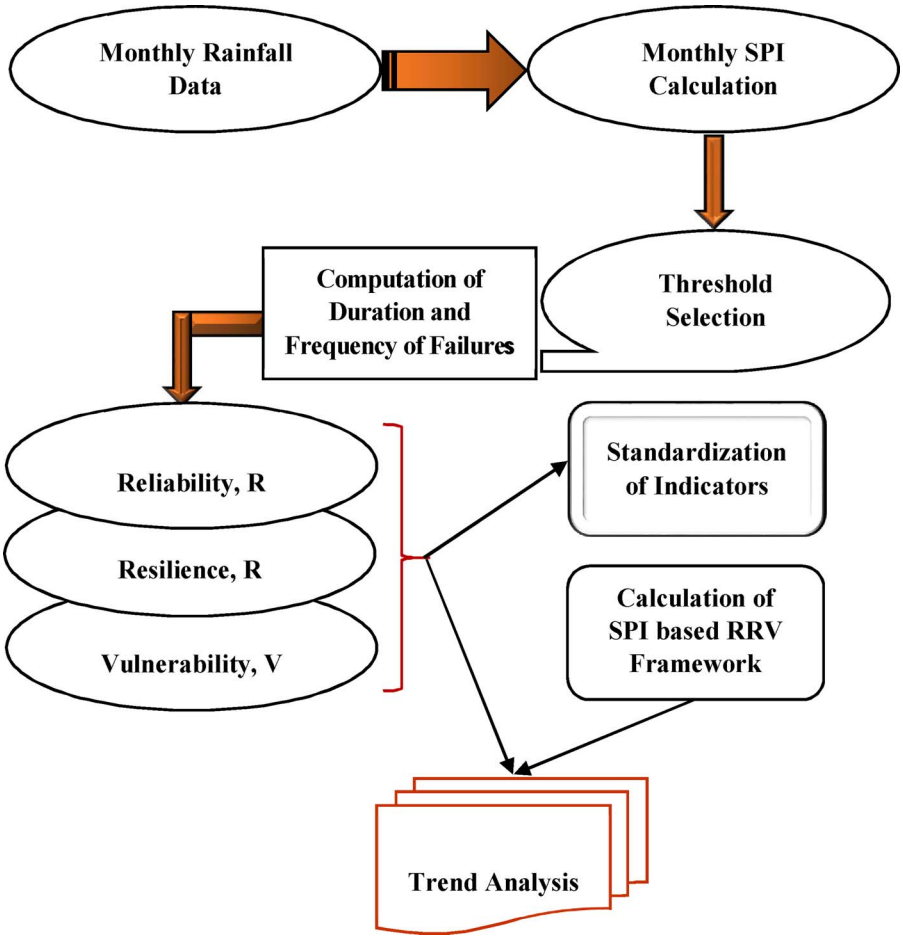

Fig. 2. Flow chart of research methodology to analyze a drought based RRV framework.

Table 1
List of selected meteorological stations and their specifications.

Study watersheds	Stations and constructed points	Longitude[a]	Latitude[a]	Mean rainfall (mm)
Foyle	Lough Fea	640613	6065487	1006
	Castlederg	591315	6062330	788
	1	599717	6067043	1146
	2	622584	6067185	1338
	3	578443	6060169	1635
	4	608961	6054180	1204
	5	597574	6049735	1187
	6	621449	6049735	1205
	7	607712	6041618	1188
Xarrama	Évora/Mitra	585810	4265277	573
	Évora/Cidade	595934	4269091	678
	Alcaçovas	574218	4249301	577
	Viana Alentejo	586931	4242554	568
	Barragem de Vale do Gaio	561926	4233238	486
Shazand	Arak	380457	3772091	305
	Astaneh	348056	3750772	464
	Emarat	368607	3748287	418
	Ghadamgah	358697	3760305	372
	Mazrae Khatun	330140	3762193	463
	Khondab	333452	3805795	288
	Gavar	377673	3759505	318
	Sarugh	361441	3808925	263

[a] Universal Transverse Mercator (UTM).

was then transformed into the standardized normal distribution (z-distribution) (Costa, 2011; Shahabfar and Eitzinger, 2013; Hosseinizadeh et al., 2015). The calculations were performed separately for each month and individual station. Similar to the percent of normal precipitation for a month, the one-month SPI was problematic to use where rainfall was abnormally distributed for a given month (Jenkins, 2012).

In order to consider the type of distribution in the calculations, the SPI time series were computed using Drought Indices Package (DIP) software (Morid et al., 2005). In this software, to calculate the SPI, a long-term precipitation record at the desired station was first fitted to a gamma distribution, which was then transformed into a normal distribution so that the mean SPI was kept at zero. The "drought" part of the SPI range was classified into "near normal ($0.99 < SPI < -0.99$)", "moderately dry ($-1.0 < SPI < -1.49$)", "severely dry ($-1.5 < SPI < -1.99$)" and "extremely dry ($SPI < -2.0$)" conditions (McKee et al., 1993, Edwards and McKee, 1997).

2.2.3. Determination of SPI threshold

To categorize the drought based RRV framework a threshold level for the SPI needed to be defined. This was accomplished by first calculating and analyzing the monthly and annual mean, median, mode and 10-year return period of the SPI for each study watershed. Then, the cumulative distribution function (CDF) was drawn as given in Fig. 3. Besides that, the given classification of SPI recommended by McKee et al. (1993) and Edwards and McKee (1997) was considered as well.

The monthly mean and median SPI calculated for Foyle and Xarrama were 0.00 and 0.02 and 0.01 and 0.01, respectively. Accordingly, a threshold SPI of −0.1 with a return period, or recurrence interval, of 15 years was chosen for these two watersheds. However, the monthly mean and median for the Shazand watershed were 0.11 and 0.13, respectively. Therefore, and in line with previous

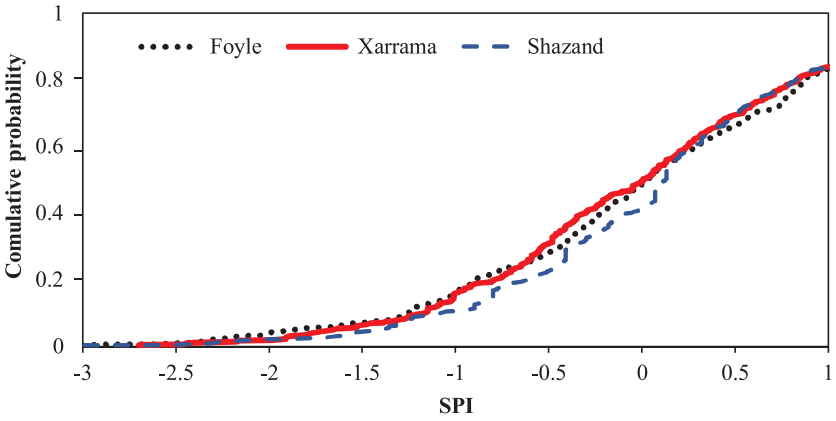

Fig. 3. Cumulative distribution function (CDF) for SPI at different study watersheds.

research (Hazbavi and Sadeghi, 2017; Sadeghi and Hazbavi, 2017), a threshold SPI of +0.1 with a return period of 15 years was selected to describe reliability, resilience and vulnerability to drought of the Shazand Watershed.

Both thresholds of +0.1 and −0.1 for the SPI fall within the near normal situation (0.99 and −0.99) for drought (McKee et al., 1993; Edwards and McKee, 1997) and were ultimately considered to be the beginning of a drought. The selected thresholds rectified the variability of the monthly SPI during the study period. It is important to mention that the one month-SPI considered for the study reflects a relatively short climatological drought and conditions of soil moisture and plant stress, mainly through the growing period.

2.2.4. Calculation of RRV indicators

The drought related RRV indicators for this study were calculated through the analysis of the temporal variation of the SPI for three climates using the following equations (Hashimoto et al., 1982 and Kjeldsen and Rosbjer, 2004).

$$Reliability(R) = 1 - \sum_{j=1}^{M} d(j) \Big/ T \tag{1}$$

$$Resilience(R) = \left\{ 1/M \sum_{j=1}^{M} d(j) \right\}^{-1} \tag{2}$$

$$Vulnerability(V) = 1/M \sum_{i=1}^{T} \left\{ \left[L_{obs}(i) - L_{std}(i) \Big/ L_{std}(i) \right] H\left[L_{obs}(i) - L_{std}(i) \right] \right\} \tag{3}$$

where M is the number of failure events (the number of months that SPI falls below the threshold), d(j) is the duration of the j^{th} failure event, T is the total number of time intervals (here 12), $L_{obs}(i)$ is the observed study constituent at the i^{th} time step, $L_{std}(i)$ is the corresponding compliance standard, and H[] is the Heaviside Function which ensures that only failure events are involved in the vulnerability calculation in Eq. (3).

A failure event was defined when SPI was below a certain threshold of SPI (here −0.1 for Foyle and Xarrama and +0.1 for Shazand) as described in the "determination of SPI threshold" section. The Heaviside function is a mathematical and discontinuous function whose value is zero for negative argument and one for positive argument. Reliability and Resilience follow a similar trend and are calculated on the probability scale, i.e., zero to one.

2.2.5. Standardization of indicators

The three indicators of RRV were calculated for every station in the study watersheds. The results were then standardized via the extreme standardization technique to range from zero to one using the following equation (Loucks, 1997; Wiegand et al., 2013; Hazbavi and Sadeghi, 2017).

$$Y = x_i - x_{min} \Big/ x_{max} - x_{min} \tag{4}$$

where, Y is the standardized value of each individual indicator; x_i is the value under consideration; and x_{min} and x_{max} are the minimal and maximal observed values, respectively.

2.2.6. Calculation and classification of drought based RRV index

The drought based RRV index was expressed by using the geometric mean (G_A) as shown in Eq. (5). The geometric mean was selected for the study, because it is more sensitive than other averages to changes in individual variables (Loucks, 1997; Cude, 2001; Wiegand et al., 2013).

$$G_A(RRV) = \left[\prod_{i=1}^{3} RRV \right]^{1/3} \tag{5}$$

A five-category classification scheme was then adopted as suggested by Ding et al. (2008) and Yu et al. (2013). After ranking the drought based RRV index from high to low, the regional drought based RRV index state was divided into five classes (I–V) named as "very high (0.81–1.00)", "high (0.61–0.80)", "moderate (0.41–0.60)", "low (0.21–0.40)" and finally "very low (0.00–0.20)". The higher the value of the drought based RRV index the better the health condition of the watershed with regard to drought.

2.2.7. Data and trend analysis

Statistical properties, viz. median, 25th and 75th percentiles, minimum, maximum and outliers in Box-Whisker plots, were used to gain further understanding and analyze the patterns of rainfall, SPI and the drought based RRV indicators in the different study watersheds.

The temporal evolution (magnitude and direction) of the two climatic variables (annual rainfall and SPI) and RRV indicators during the period 1981–2012 were assessed for each watershed. The Mann-Kendall statistical test (Mann, 1945; Kendall, 1975) was applied for annual rainfall, SPI, RRV indicators and the drought based RRV index using XLSTAT (Sadeghi and Hazbavi, 2015). The Mann-Kendall test has been used frequently to quantify the significance of trends in climatic and hydrometeorological time series (e.g., Murphy et al., 2013; Sadeghi and Hazbavi, 2015; Davudirad et al., 2016). The trends were assessed by applying the Kendall's tau ranking correlation coefficient and corresponding level of significance.

Statistical analysis of differences among the three study watersheds in regards to rainfall, SPI, RRV indicators and drought based RRV index was conducted by one-way analysis of variance (ANOVA) and Kruskal-Wallis tests (Jien and Wang, 2013; Sadeghi et al., 2016b; Bihamta and Zare Chahouki, 2015) for 32 years- data series. The normality and homogeneity of variances of the indicators in different study areas were tested using the Kolmogrov-Smirnov and Levene tests, respectively

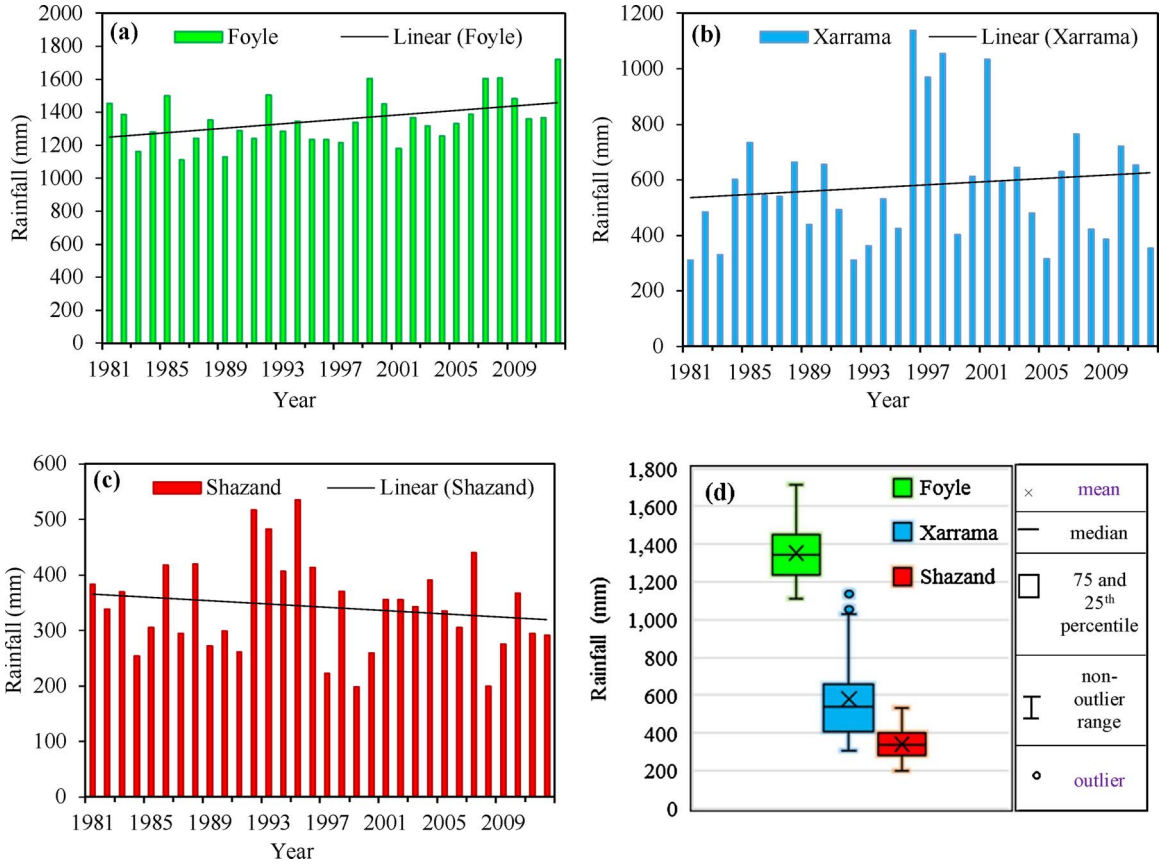

Fig. 4. Variability and trend of mean annual rainfall for Foyle (a), Xarrama (b) and Shazand (c) watersheds and Box-Whisker plot of rainfall (d) for the period 1981–2012.

(Bihamta and Zare Chahouki, 2015) at 0.05 level of significance. Significant means were also subjected to further analysis by Duncan's multiple range test for normal and homogenous data as well as the Kruskal-Wallis (Chi-square) nonparametric test for abnormal and non-homogenous data ($P < 0.05$) (Sadeghi et al., 2014; Hazbavi and Sadeghi, 2015; Sadeghi et al., 2016a; Bihamta and Zare Chahouki, 2015). The entire statistical analyses of data were done using SPSS version 22 Software.

3. Results

3.1. Rainfall and SPI

Mean annual rainfall varied from 1113 to 1719 mm in the Foyle Watershed, from 310 to 1138 mm in the Xarrama Watershed and from 198 to 535 mm for the Shazand Watershed (Fig. 4). The corresponding annual SPI values ranged from −1.76 to 2.38, −1.45 to 2.22 and −1.99 to 2.24 for Foyle, Xarrama and Shazand, respectively with mean values of −0.001 ± 1.02, −0.002 ± 1.02 and 0.083 ± 1.07 (Fig. 5).

The results of the trend test showed a significant (P-value < 0.009) increasing trend for rainfall and SPI for Foyle and a non-significant (P-value = 1.00) increasing trend for rainfall and SPI for Xarrama. A non-significant (P-value > 0.40) decreasing trend for both rainfall and SPI was found for the Shazand Watershed (Figs 4c and Fig. 55c). The distribution of annual rainfall and SPI for Foyle and Xarrama shown in Figs. 4d and 5d has a positive skew, while the rainfall and SPI appears to be close to symmetric for the Shazand Watershed.

Statistical analyses showed a significant rainfall gradient from the temperate to Mediterranean to semiarid climates (Chi-square = 74.48; df = 2.00; P-value = 0.00) despite of a non-significant SPI gradient (F = 0.071; df = 2; P-value = 0.93).

3.2. Reliability, resilience and vulnerability (RRV) indicators

In the Irish watershed, the mean RRV indicators were categorized in the moderate status (0.45 ± 0.28, 0.51 ± 0.26 and 0.86 ± 0.18, respectively) throughout the study period (Figs. 6a, 7a and 8a). A non-significant (P > 0.12) increasing trend was observed for reliability and resilience and a non-significant (P > 0.16) decreasing trend was observed for vulnerability.

Figs. 6b, 7b and 8b show the results for the Xarrama watershed, for which mean values of the RRV indicators were found to be 0.49 ± 0.27, 0.49 ± 0.23 and 0.82 ± 0.20, respectively. Overall, non-significant increasing trends for reliability and resilience and a decreasing trend for vulnerability (P-value > 0.75) were observed as shown in Figs. 6b, 7b and 8b.

For the Shazand Watershed mean RRV indicators of 0.49 ± 0.24, 0.47 ± 0.25 and 0.21 ± 0.24 were found, respectively (Figs. 6c, 7c and 8c). The results of the trend test showed a non-significant decreasing trend for reliability and resilience (P-value > 0.95) as presented in Figs. 6c and 7c, while a non-significant increasing trend was detected for vulnerability (P-value > 0.94) (Fig. 8c).

Each of the Box-Whisker plot in Figs. 6d, 7d and 8d show different skewness patterns. Most of the reliability data were concentrated on the high end of the scale for Foyle and Xarrama watersheds and the distribution was skewed positive. However, the reliability observations split approximately at the median for the Shazand Watershed and the distribution seemed fairly symmetric (Fig. 6d). The distributions of resilience shown in Fig. 7d for Foyle and Xarrama were close to symmetric and positively skewed, respectively. However, the mean resilience for the Shazand Watershed was found lower than the median and hence negatively skewed. The distribution of vulnerability for the Foyle and Xarrama watersheds shown in Fig. 8d had a highly negative skewness, with the mean vulnerability being smaller than the median

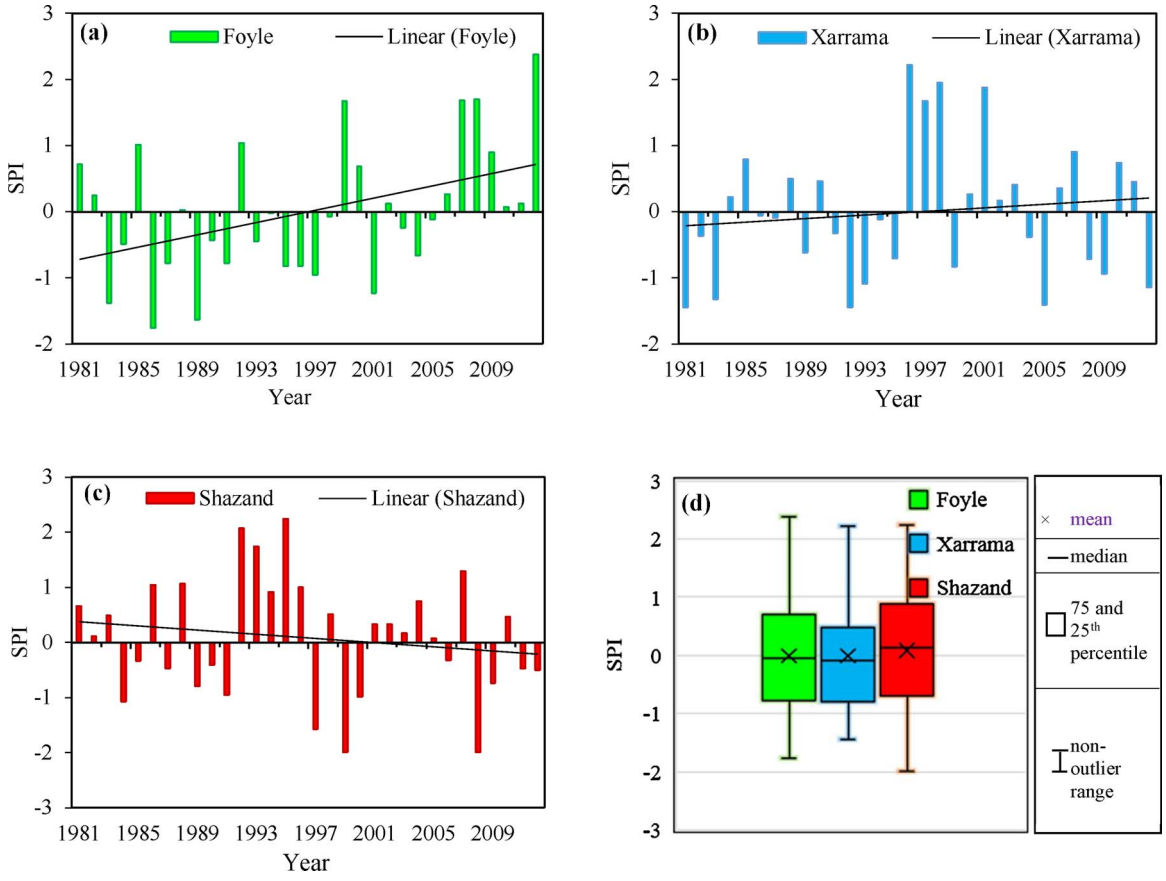

Fig. 5. Variability and trend of mean annual SPI for Foyle (a), Xarrama (b) and Shazand (c) watersheds and Box-Whisker plot of SPI (d) for the period 1981–2012.

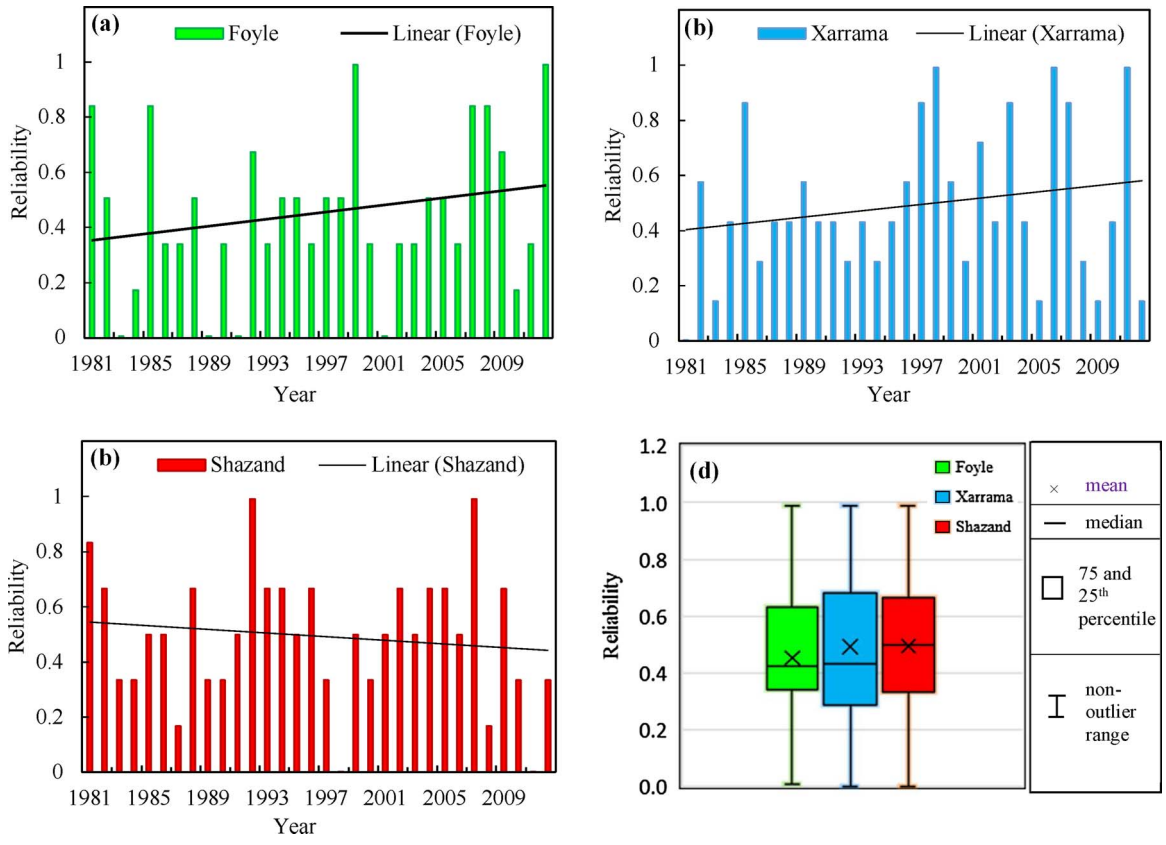

Fig. 6. Variability and trend of drought based reliability indicator for Foyle (a), Xarrama (b) and Shazand (c) watersheds and Box-Whisker plot of reliability (d) for the period 1981–2012.

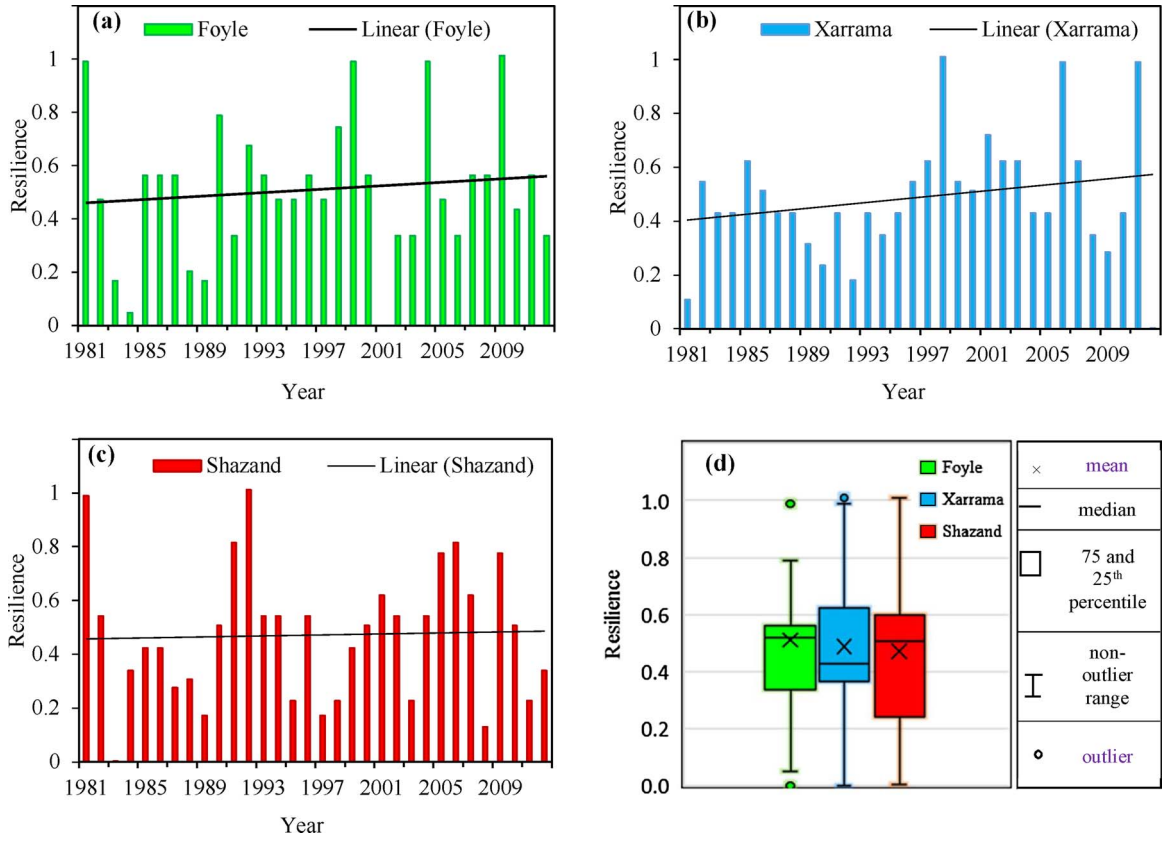

Fig. 7. Variability and trend of drought based resilience indicator for Foyle (a), Xarrama (b) and Shazand (c) watersheds and Box-Whisker plot of resilience (d) for the period 1981–2012.

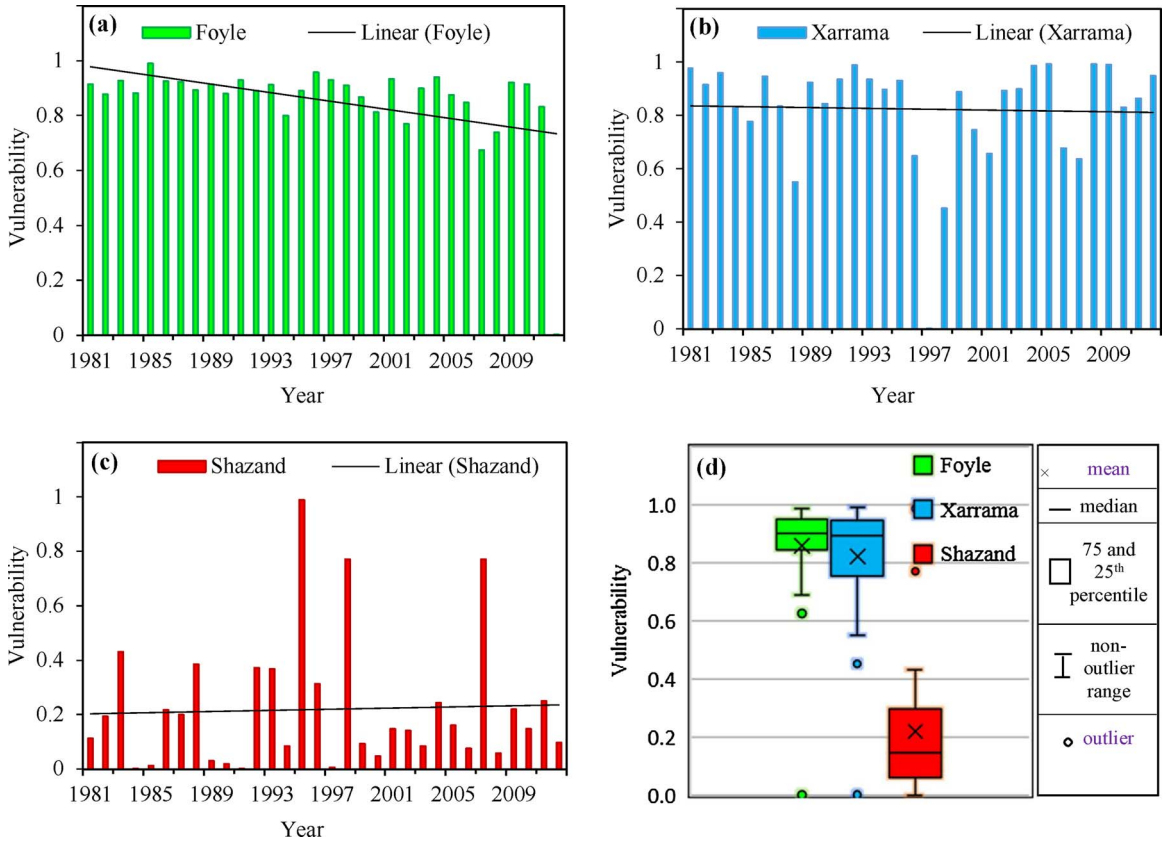

Fig. 8. Variability and trend of drought based vulnerability indicator for Foyle (a), Xarrama (b) and Shazand (c) watersheds and Box-Whisker plot of vulnerability (d) for the period 1981–2012.

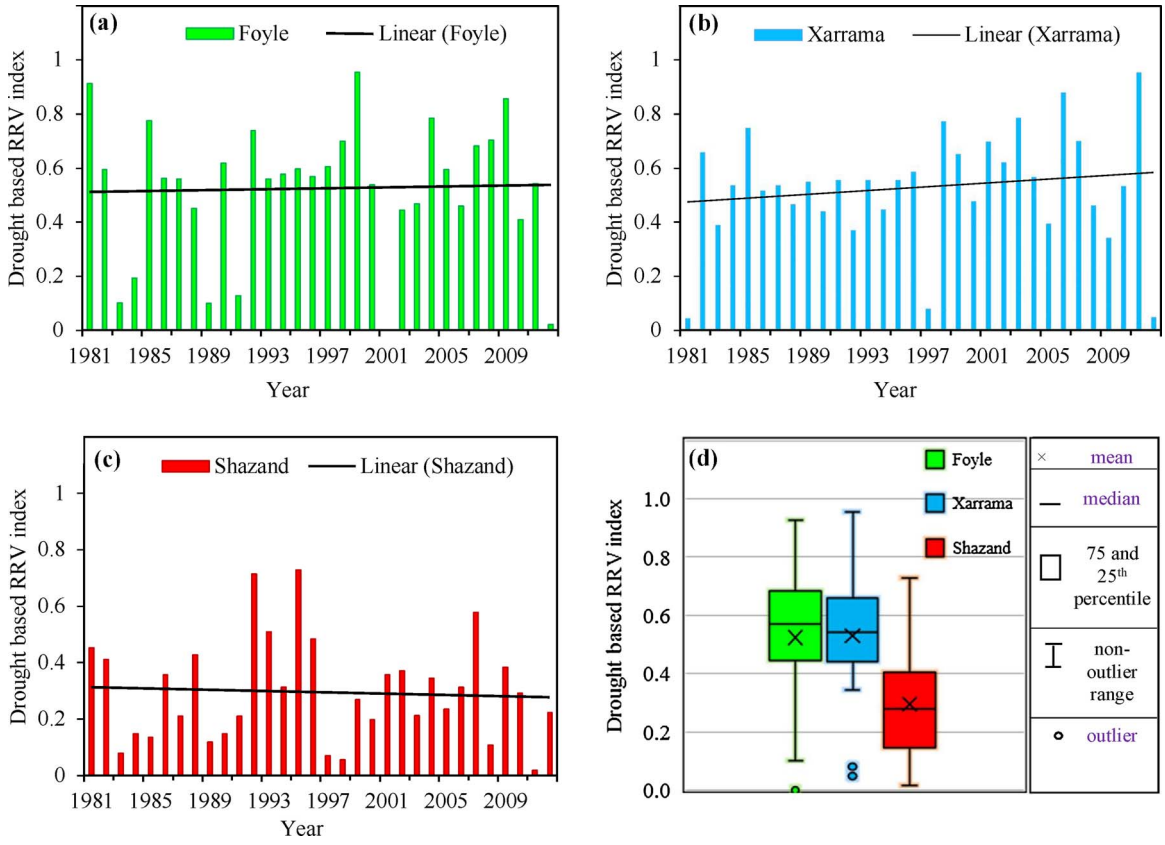

Fig. 9. Variability and trend of drought based RRV index for Foyle (a), Xarrama (b), Shazand (c) watersheds and Box-Whisker plot of drought based RRV index (d) for the period 1981–2012.

and with limited outliers in the low end. By contrast, for the Shazand Watershed, the distribution of vulnerability was positively skewed.

Kruskal-Wallis analysis showed that the reliability (Chi-square = 0.05; df = 2.00; P-value = 0.98) and resilience (Chi-square = 0.92; df = 2.00; P-value = 0.63) indicators didn't change significantly across the climatological gradient from temperate to Mediterranean and semi-arid. However, the vulnerability indicator was significantly influenced by the study climatic gradient (Chi-square = 47.45; df = 2.00; P-value = 0.00).

3.3. Drought based RRV index

The results of the geometric mean drought based RRV index for the Foyle, Xarrama and Shazand watersheds were computed as 0.52 ± 0.25, 0.53 ± 0.21, and 0.30 ± 0.18, respectively. The drought based RRV index obtained for Foyle and Xarrama was higher than that for Shazand Watershed (Fig. 9).

A non-significant increasing trend was found for the drought based RRV index for the period 1981–2012 for Foyle and Xarrama watersheds (P-value > 0.52) and a non-significant decreasing trend for Shazand Watershed (P-value > 0.48) (Fig. 9).

The Box-Whisker plots for the drought based RRV index showed a negative skewness for Foyle and Xarrama watersheds and a positive skewness for the Shazand Watershed (Fig. 9d). As seen in the Box-Whisker plots there are very limited outliers for rainfall, SPI and RRV indicators.

With the three watershed health risk (RRV) indicators incorporated, the climatological gradient did significantly affect the drought based RRV index, with Chi-Square, df and P- values of 21.47, 2.00 and 0.00, respectively.

4. Discussion

4.1. Rainfall and SPI analyses

The significant positive trend of yearly rainfall for the Foyle Watershed corroborate the findings of McElwain and Sweeney (2003), Sheridan, McElwain and Sweeney, Kiely et al. (2010). Extreme rainfall events have become more common in Ireland since 1975 and have been correlated with an increase in the positive phase of the North Atlantic Oscillation (NAO) (Kiely, 1999). Some studies (e.g., Jones and Conway, 1997; Murphy and Washington, 2001) have reported that Irish winters became wetter and summers drier, particularly over the 1977–1997 period. Additionally, OSI (2010), Murphy et al. (2013) and McClatchey (2014) reported extended drought conditions in the early 1970s which weakened the strength and significance of flow trends from this period onwards. Overall, droughts have been rare in Ireland, as measurable rainfall always occurred somewhere in the synoptic network in every month since the 1940s. The longest absolute drought was recorded in Limerick from 3 April to 10 May 1938. Notwithstanding, some memorably dry summers occurred, most notably the 'summer of the century' in 1995 and, to a lesser extent, in 2006 when only 89 mm of rain was recorded at Shannon during the three summer months (McClatchey, 2014).

A seesaw tendency for rainfall and SPI has been reported for the Mediterranean region (IPCC, 2007; Santo et al., 2014). The results of this study for rainfall and SPI agree with several other findings of changes in precipitation for watersheds in southern Portugal (e.g., Trigo and DaCamara, 2000; Paredes et al., 2006; de Lima et al., 2007, 2010). The trends we found for rainfall and SPI were not statistically significant owing to the large temporal variability. Results of Corte-Real et al. and da Silva et al. (2015) showed that these variations matched fluctuations in the frequencies of occurrence of both the rainy and the

dry patterns. Four weather circulation patterns, viz. blocking-like, summer dry, winter dry and rainy, were important for investigating regional climate change in Portugal and its relationship with variability of large-scale atmospheric circulation. Furthermore, the trend of reduction of occurrence of the rainy pattern was closely related to the variation of the intensity of the NAO. Therefore, it could be concluded that these variations and phenomena greatly affected the computed RRV indicators. Additionally, Costa and Soares (2009) verified significant trends towards drier climatic conditions in many stations located in the south of Portugal during the 1955–1999 period. An increase in dry years in the northeast area and a decrease in wet years with a consequent increase of normal years was found in the southeast sector of Alentejo during the period 1931–2006 (Mourato et al., 2010). It was concluded that this was a result of changes in the precipitation regime. We suggest that more attention needs to be given to drought trends during the agricultural development and water resource management decision-making process in these areas.

The Shazand Watershed is located in a semiarid region (Hazbavi and Sadeghi, 2017; Sadeghi and Hazbavi, 2017) where more knowledge on climatic behavior is needed for water resources management (da Silva et al., 2015). Examination of annual rainfall and SPI in the period 1981–2012 showed that the Shazand watershed encountered frequent droughts (Figs. Fig. 44c and 5c). This finding is consistent with Abtahi and Safe (2012) who noted that Arak City, some 40 km from the study watershed, also experienced harsh droughts between 1956 and 2005. Recently, Damavandi et al. (2016) additionally verified that droughts have caused serious challenges in much of Markazi Province, especially in the areas where the variability in annual rainfall was high. To reduce the impact of drought in the Shazand Watershed and develop more resilience to climate oscillation or change, there is a need for raising awareness at local and regional levels and public policy to develop adaptive management strategies.

4.2. RRV framework analysis

The results of RRV indicators for the Foyle and Xarrama watersheds (Figs. 5a, 6a and 7a) indicated relatively good chance of a quick recovery in the event of an instance of SPI threshold violation. This is not surprising in light of the high amount of rainfall in these study regions. Change in the frequency of rainfall events and changes in the intensity of rainfall per event, or a combination of both, affected variations in SPI based RRV indicators. Nature, magnitude, frequency, and severity of rainfall and consequently SPI were the main reasons behind the results and caused similar results despite different governing climatic conditions for Foyle and Xarrama. Results of the drought based RRV framework approach indicated that the Shazand Watershed (reliability = 0.49; resilience = 0.47; vulnerability = 0.22) had the highest threat of drought.

In Fig. 6d, it can be seen that the three watersheds had very similar median reliability values (i.e., 0.40–0.50). In detail, the median reliability for Foyle (0.42) and Xarrama (0.43) were nearly identical. Nonetheless, the behavior of reliability for Shazand (0.50) was slightly different. Reliability is influenced by the duration of failure events (d) and total number of time intervals (T). Here, the T factor was equal (i.e., 12) for all watersheds. This implies that the duration of failure events was the factor affecting the reliability of watersheds for droughts. According to the analysis, the *d* value was very variable in the study years for the three watersheds, but the dynamic interaction of the watersheds was neutralized and then balanced over the long-term causing almost similar reliability behavior for three study watersheds despite the different climatic conditions. This result means that the variability was averaged out when looking at the entire temporal scale.

The resilience indicator for Foyle and Xarrama was less variable than that of Shazand due to rainfall anomaly (Fig. 7d). The resilience indicator was influenced by the duration of failure (d) and number of failure events (M). Interaction of these factors during the 1981–2012 period caused a similar median resilience against droughts for Foyle (0.52) and Shazand (0.51). However, a lower median resilience of 0.43 was found for Xarrama (Fig. 7d).

The vulnerability indicator was found to be the smallest for the Shazand Watershed. The lower vulnerability value is consistent with the corresponding low value of SPI. In the Shazand Watershed, with an arid climate, the summer months did not have rainfall, leading to more negative SPI values in summer and also some spring months compared to Foyle and Xarrama. Therefore, the higher severity of SPI in some months in Foyle and Xarrama caused the higher vulnerability value.

The Box-Whisker plots suggest that there is more spread or variation in the reliability responses for Xarrama and resilience and vulnerability responses for Shazand. In addition, the median values did not occur in the same place in each box, indicating that the three watersheds did not have similar shapes. Overall, these findings suggested that the rainfall anomaly affected the responses of the indicators for three study watersheds. Accordingly, the integrity of the RRV indicators had high necessity to draw comprehensive assessment about function and structure of the watersheds with respect to rainfall variability and drought context.

In the case of the integrated drought based RRV index, the median was found to be very similar for Foyle (0.57) and Xarrama (0.54), whereas a much smaller value was found for Shazand (0.28). The integrated drought based RRV index was also found to be more variable for the Shazand Watershed compared to the other two watersheds (Fig. 9). This indicates that drought was less serious in the Foyle and Xarrama watersheds. These differences could be related to the climate and rainfall variability (Fig. 4) of the study watersheds.

Applying the drought based RRV framework has shown that climatic conditions and rainfall variability are important drivers of droughts. It can be concluded that the endogenous driver of extreme weather conditions included prolonged periods of lower mean rainfall and anomalously low summer rainfall in the Shazand Watershed, resulting in the much lower drought based RRV index.

For the Portuguese Watershed, extreme precipitation events have raised concerns about the risks of land degradation and desertification as reported by Lázaro et al. (2001), de Lima et al. (2002), Costa et al. (2008) and de Lima et al. (2013). Furthermore, the desertification susceptibility map of Portugal's National Action Programme to Combat Desertification shows that, under the mean climatic regime evaluated, the south of the country has extensive areas that are highly vulnerable to desertification. Accordingly, research on the extent of dryness and space-time patterns of extreme precipitation is an important contribution to evaluating desertification dynamics in this region (Costa, 2011). The mean drought based RRV index (0.53) for the Xarrama Watershed indicates a moderate response to droughts (Fig. 9). These results are in agreement with the findings of de Lima et al. (2002) and de Lima et al. (2013), who stated that the southern region of mainland Portugal was probably more prone than other regions of the country to an aggravation of heavy precipitation events due to the climate change.

The mean RRV indicators (Fig. 8) and drought based RRV index (Fig. 9) indicate a serious (0.21–0.40) threat for the health of the Shazand Watershed with respect to drought, and suggest a need for adaptive measures to increase the reliability and resilience and decrease the vulnerability of the watershed to drought. Moderate and low drought classes have been also reported for the Shazand Watershed by Damavandi et al. (2016), and Hazbavi and Sadeghi (2017). The health of the Shazand Watershed from the view point of the SPI in the node years of 1986, 1998, 2008 and 2014 also shows the poor status of the watershed, resulting in it not being able to recover from the rainfall decreases (Sadeghi and Hazbavi, 2017). The low drought based RRV index value means that the system is not in a condition to reliably satisfy the demands on it and is prone to water scarcity. It is therefore suggested that a mixture of protection, effective management and restoration would be utilized to maintain the drinking water supplies in the whole study watersheds.

In this study the rainfall gradient was found to be relevant and affected the health indicators. The vulnerability of the watershed and the drought based health index were most influenced by the climatological gradient factors i.e., altitude, topography, temperature and precipitation (Sternberg et al., 2011), which is in line with the findings of other researches (e.g., Cerdà, 1998a, 1998b; Sternberg et al., 2011). Thereinto, climatic gradients provide a useful framework for studying the effects of climate change (Sternberg et al., 2011). These risk-based analyses will help water authorities including watershed organizations and water utilities, assess existing situations, plan for future scenarios, implement processes and thus increase efficiency of the future programs. It also help suggest planting high-yield, high-value and drought-tolerant crops. Plans for a response to droughts should be devised in advance for the most effective measures to be applied and the distress from unexpected water limitations held to a minimum. Though governments are responsible, it is vital that the public and all water consumers contribute in formulating practical plans. Elements of all drought management plans, should be incorporated into study watersheds even with moderately drought prone watersheds like Foyle (Frederiksen, 1992).

4.3. Advantages and limitations of RRV framework

A key advantage of the RRV framework approach is the ability to combine and quantify risk indicators, viz. reliability, resilience and vulnerability. Nowadays, more attention is being given to the development of composite frameworks to quantify different ecosystem dimensions due to different drivers. The RRV framework approach fits well within this pattern providing greater clarity, consistency and application of environmental factors. This advantage can and must be balanced with more generalized and integrated environment assessment studies. Additionally, the drought based RRV framework is not excessively time consuming and the data needed is relatively easy to obtain and process. Consequently, the results can be very helpful to elementary health assessments of watersheds.

One disadvantage of the RRV framework is its inapplicability for thresholds of zero. The most critical factor in this framework is threshold selection, as by using a different threshold, the results will be different. More research is needed into choosing the threshold level for different hydroclimatic regions. Towards this aim, sensitivity analysis, which was beyond the scope of the present paper, is suggested as an approach to assess the sensitivity of the RRV framework to different SPI thresholds.

5. Summary and conclusions

This study involves novelty of proposing the watershed drought concept for evaluating rainfall time series and demonstrated the concept, for the first time, by identifying the most sustainable rainfall series following the RRV conceptual framework. A climatological gradient from temperate to Mediterranean to semiarid was included through study site selection to increase the scientific relevance of the findings. To this end, a study on the behavior of RRV indicators in the context of drought was carried out in three watersheds selected from three different climatic conditions in Europe and Asia. Since, the detection of changes in trends and responses provides valuable information for future watershed management, this study aimed to identify possible rainfall, SPI and RRV trends in study watersheds using the Mann-Kendall test. Monthly precipitation data for over 32 years from three watersheds was used.

The most important findings of the study are the followings:

- The drought based RRV index calculated for the watersheds in the temperate and Mediterranean climates, Foyle and Xarrama, was in the medium category (0.4–0.6) with values ranging between 0.52 and 0.53, while for the Shazand Watershed in the semiarid climate it was in the poor category (0.2–0.4) with a value of 0.30 (reliability = 0.49; resilience = 0.47; vulnerability = 0.22). These values are in general agreement with other assessments of these areas, indicating that the proposed approach is effective.
- The use of Box-Whisker plots showed that there is more spread or variation in the reliability responses for Xarrama and more spread in the resilience and vulnerability responses for Shazand. Additionally, the drought based RRV index showed the negative skewness for Foyle and Xarrama and positive skewness for Shazand.
- Nature, magnitude, frequency, and severity of rainfall and consequently SPI were the main factors influencing the results and leading to similar results for Foyle and Xarrama despite different governing climatic conditions.
- We found that there was no meaningful quantitative relationship between the drought based RRV framework and climate. However, it was found that there were meaningful and different temporal trends in the drought based RRV framework applied to the rainfall data during the period 1981–2012.
- The statistical analyses verified a significant climatological gradient with respect to rainfall from the temperate climate (Foyle Watershed) to the Mediterranean (Xarrama Watershed) and ultimately to semi-arid (Shazand Watershed) climates.
- The SPI, and reliability and resilience indicators were not significantly influenced by climatic gradient. However, the watershed vulnerability and drought based RRV index were significantly affected by climatological gradient.
- Finally, the application of the RRV framework for assessing watershed status in connection with climate change and other drivers and stressors is in its infancy conceptually and in application. The theory and practice of regional drought assessment using the RRV conceptual framework has promise, but needs to be evolved and improved. There is still much to learn in connection with the RRV framework about how to set goals, plan actions, select criteria thresholds, apply resources, manage, evaluate, and learn adaptively in light of uncertainty and ecological and social dynamics.
- Our recommendations for continuing development of this approach include the use of multiple statistical means (at least two) in combining the RRV indicators to compare the results, the application of the RRV framework to different time scales of SPI, investigation of the responses of the RRV indicators to different SPI thresholds, and application of this framework using other meteorological indicators at various time scales to allow drawing more comprehensive conclusions.

Acknowledgements

The present paper has been prepared based on the facilities and information provided during the sabbatical leave of the Miss. Z. Hazbavi, Ph.D. Candidate in Watershed Management Sciences and Engineering at Tarbiat Modares University in Iran, at Physics and Land Management Group, Wageningen University and Research during November 2016 to May 2017 in the Netherlands whose valuable supports of both universities are acknowledged. The authors would like to express their appreciation to Demie Moore (Wageningen University and Research) for improving the text and anonymous reviewers for the helpful comments and constructive suggestions.

References

Abtahi, S.M., Safe, A., 2012. Rain and temperature trends in Namak Lake Basin (Iran), during the last half-century. Int. J. Sci. Nat. 3 (1), 137–146.
Asefa, T., Clayton, J., Adams, A., Anderson, D., 2014. Performance evaluation of a water resources system under varying climatic conditions: reliability, resilience, vulnerability and beyond. J. Hydrol. 508, 53–65.
Bihamta, M.R., Zare Chahouki, M.A., 2015. Principles of Statistics for the Natural Resources Science, Fourth edition. University of Tehran Press 300 p (In Persian).
Cerdà, A., 1998a. Effect of climate on surface flow along a climatological gradient in

Israel: a field rainfall simulation approach. J. Arid Environ. 38 (2), 145–159.
Cerdà, A., 1998b. Relationships between climate and soil hydrological and erosional characteristics along climatic gradients in Mediterranean limestone areas. Geomorphology 25 (1–2), 123–134.
Chanda, K., Maity, R., Sharma, A., Mehrotra, R., 2014. Spatiotemporal variation of long-term drought propensity through reliability-resilience-vulnerability based drought management index. Water Resour. Res. 50, 7662–7676.
Chen, S.T., Kuo, C.C., Yu, P.S., 2009. Historical trends and variability of meteorological droughts in Taiwan/tendances historiques et variabilité des sécheresses météorologiques à Taiwan. Hydrol. Sci. J. 54 (3), 430–441.
Costa, A.C., Soares, A., 2009. Trends in extreme precipitation indices derived from a daily rainfall database for the south of Portugal. Int. J. Climatol. 9, 1956–1975.
Costa, A.C., Durão, R., Pereira, M.J., Soares, A., 2008. Using stochastic space-time models to map extreme precipitation in southern Portugal. Nat. Hazards Earth Syst. Sci. 8, 763–773.
Costa, A.C., 2011. Local patterns and trends of the standard precipitation index in southern Portugal (1940–1999). Adv. Geosci. 30, 11–16.
Cude, C.G., 2001. Oregon water quality index: a tool for evaluating water quality management effectiveness. J. Am. Water Resourc. Assoc. 37, 125–137.
da Silva, R.M., Santos, C.A.G., Moreira, M., Corte-Real, J., Silva, V.C.L., Medeiros, I.C., 2015. Rainfall and river flow trends using Mann–Kendall and Sen's slope estimator statistical tests in the Cobres River basin. Nat. Hazards 77, 1205–1221.
Damavandi, A.A., Rahimi, M., Yazdani, M.R., 2016. Assessment of drought severity using vegetation temperature condition index (VTCI) and Terra/MODIS satellite data in rangelands of Markazi Province, Iran. J. Rangeland Sci. 6 (1), 33–42.
Darabi, H., Shahedi, K., Solaimani, K., Miryaghoubzadeh, M., 2014. Prioritization of subwatersheds based on flooding conditions using hydrological model, multivariate analysis and remote sensing technique. Water Environ. J. 28, 382–392.
Davudirad, A.A., Sadeghi, S.H.R., Sadoddin, A., 2016. The Impact of development plans on hydrological changes in the Shazand Watershed, Iran. Land Degrad. Develop. 27, 1236–1244.
de Lima, M.I.P., Schertzer, D., Lovejoy, S., de Lima, J.L.M.P., 2002. Multifractals and the study of extreme precipitation events: a case study from semiarid and humid regions in Portugal. In: Singh, V.P., Al-Rashid, M., Sherif, M.M. (Eds.), Surface Water Hydrology. A.A. Balkema Publishers, Swets and Zeitlinger B.V., Lisse, The Netherlands, pp. 195–211.
de Lima, M.I.P., Marques, A.C.P., de Lima, J.L.M.P., Coelho, M.F.E.S., 2007. Precipitation trends in Mainland Portugal in the period 1941–2000. IAHS Publ., 310. Int. Assoc. Hydrol. Sci. 94–102.
de Lima, M.I.P., Carvalho, S.C.P., de Lima, J.L.M.P., 2010. Investigating annual and monthly trends in precipitation structure: an overview across Portugal. Nat. Hazards Earth Syst. Sci. 10, 2429–2440.
de Lima, M.I.P., Santo, F.E., Ramos, A.M., de Lima, J.L.M.P., 2013. Recent changes in daily precipitation and surface air temperature extremes in mainland Portugal, in the period 1941–2007. Atmos. Res. 127, 195–209.
Ding, Y., Wang, W., Cheng, X., Zhao, S., 2008. Ecosystem health assessment in Inner Mongolia Region based on remote sensing and GIS. In: Beijing. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences Vol. XXXVII. pp. 1029–1034 Part B1.
Edwards, D.C., McKee, T.B., 1997. Characteristics of 20th century droughts in the United States at multiple time scales. Climatology Report, 97-2. Department of Atmospheric Sciences. Colorado State University, Fort Collins 155 p.
Esfahanian, E., Nejadhashemi, A.P., Abouali, M., Adhikari, U., Zhang, Z., Daneshvar, F., Herman, M.R., 2017. Development and evaluation of a comprehensive drought index. J. Environ. Manage. 185, 31–43.
Frederiksen, H.D., 1992. Drought Planning and Water Efficiency Implications in Water Resources Management. World Bank Technical Paper. ISSN 0253-7494, no. 185, 50 p.
Freire-González, J., Decker, C., Hall, J.W., 2017. The economic impacts of droughts: a framework for analysis. Ecol. Econ. 132, 196–204.
Galván, L., Olías, M., Izquierdo, T., Cerón, J.C., 2014. Rainfall estimation in SWAT: an alternative method to simulate orographic precipitation. J. Hydrol. 509, 257–265.
García-Garizábal, I., Causapé, J., Abrahao, R., Merchan, D., 2014. Impact of climate change on Mediterranean irrigation demand: historical dynamics of climate and future projections. Water Resour. Manage. 28, 1449–1462.
Hashimoto, T., Loucks, D.P., Stedinger, J., 1982. Reliability, resilience and vulnerability for water resources system performance evaluation. Water Resour. Res. 18, 14–20.
Hazbavi, Z., Sadeghi, S.H.R., 2017. Watershed health characterization using reliability-resilience-vulnerability conceptual framework based on hydrological responses. Land Degrad. Develop. 28, 1528–1537.
Herath, G., Hasanov, A., 2017. Climate Change and Threats to Sustainability in South East Asia: Dynamic Modelling Approach for Malaysia. In Regional Growth and Sustainable Development in Asia. Springer International Publishing, pp. 133–148.
Hoque, Y.M., Tripathi, S., Hantush, M.M., Govindaraju, R.S., 2012. Watershed reliability, resilience and vulnerability analysis under uncertainty using water quality data. J. Environ. Manage. 10, 101–112.
Hoque, Y.M., Tripathi, S., Hantush, M.M., Govindaraju, R.S., 2016. Aggregate measures of watershed health from reconstructed water quality data with uncertainty. J. Environ. Qual. 45, 709–719.
Hosseinizadeh, A., SeyedKaboli, H., Zareie, H., Akhondali, A., Farjad, B., 2015. Impact of climate change on the severity, duration, and frequency of drought in a semi-arid agricultural basin. Geoenviron. Disasters 2 (23), 9.
IPCC Intergovernmental Panel on Climate Change, 2007. Climate change 2007: the physical science basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge 996 p.
IPCC, Intergovernmental Panel on Climate Change, 2014. Climate change 2014: synthesis report. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland 151 p.
Jain, S.K., Bhunya, P.K., 2008. Reliability, resiliency, and vulnerability of a storage reservoir. Hydrol. Sci. J. 53, 434–447.
Jain, S.K., 2010. Investigating the behavior of statistical indices for performance assessment of a reservoir. J. Hydrol. 391, 90–96.
Jenkins, K., 2012. Modelling the Economic and Social Consequences of Drought Under Future Projections of Climate Change. Ph.D. Dissertation. University of Cambridge 222 p.
Jien, S.H., Wang, C.S., 2013. Effects of biochar on soil properties and erosion potential in a highly weathered soil. Catena 110, 225–233.
Jones, P.D., Conway, D., 1997. Precipitation in the British Isles: an analysis of area-averaged data updated to 1995. Int. J. Climatol. 17, 427–438.
Kendall, M.G., 1975. Rank Correlation Methods, 4th ed. Charles Griffin, London.
Keyantash, J., Dracup, J.A., 2002. The quantification of drought: an evaluation of drought indices. Bull. Am. Meteorol. Soc. 83 (8), 1167–1180.
Khan, S., Gabriel, H.F., Rana, T., 2008. Standard precipitation index to track drought and assess impact of rainfall on water tables in irrigation areas. Irrig. Drainage Syst. 22 (2), 159–177.
Kiely, G., Leahy, P., Ludlow, F., Stefanini, B., Reilly, E., Monk, M., Harris, J., 2010. Extreme Weather, Climate and Natural Disasters in Ireland. EPA (2007-CCRO-2,7). Available from: http://erc.epa.ie/safer/reports 46 p.
Kiely, G., 1999. Climate change in Ireland from precipitation and streamflow observations. Adv. Water Resour. 23, 141–151.
Kjeldsen, T.R., Rosbjer, D., 2004. Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems. Hydrol. Sci. J. 49, 755–767.
Lázaro, R., Rodrigo, F.S., Gutiérrez, L., Domingo, F., Puigdefábregas, J., 2001. Analysis of a 30-year rainfall record (1967–1997) in semi-arid SE Spain for implications on vegetation. J. Arid. Environ. 48, 373–395.
Loucks, D.P., 1997. Quantifying trends in system sustainability. Hydrol. Sci. J. 42 (4), 513–530.
Loukas, A., Vasiliades, L., 2005. Identification of the relationship between meteorological and hydrological drought. Geophys. Res. Abstr. 7, 05479.
Maier, R.H., Lence, J.B., Tolson, A.B., Foschi, R.O., 2001. First-order reliability method for estimating reliability, vulnerability, and resilience. Water Resour. Res. 37, 779–790.
Maity, R., Sharma, A., Nagesh Kumar, D., Chanda, K., 2013. Characterizing drought using the reliability-resilience-vulnerability concept. J. Hydraul. Res. 18, 859–869.
Mann, H.B., 1945. Non-parametric tests against trend. Econometrica 13, 245–259.
McClatchey, J., 2014. Regional weather and climates of the British Isles – part 9: Scotland. Weather 69 (10), 275–281.
McElwain, L., Sweeney, J., 2003. Climate change in Ireland- recent trends in temperature and precipitation. Irish Geogr. 36, 97–111.
McKee, T.B.N., Doesken, J., Kliest, J., 1993. The relationship of drought frequency and duration to time scales. In: 8th Conference on Applied Climatology. Anaheim CA, American meteorological Society, Washington DC. pp. 179–184.
McMichael, A.J., Campbell-Lendrum, D.H., Corvalán, C.F., Ebi, K.L., Githeko, A., Scheraga, J.D., Woodward, A., 2003. Climate Change and Human Health: Risks and Responses. World Health Organisation ISBN 92 4 156248 X, 322 P.
Mokhtari, Sh., Babazadeh, H., Sedghi, H., Kaveh, F., 2011. Long term simulation of Shazand Plain Aquifer under changing resources and applications. Int. J. Agric. Sci. Res. 2, 1–10.
Mondal, M.S., Chowdhury, J.U., Ferdous, M.R., 2009. Risk based evaluation for meeting future water demand of the Brahmaputra Floodplain within Bangladesh. Water Resour. Manage. 24 (5), 853–869.
Morid, S., Moghaddasi, M., Arshad, S., Omid, M., 2005. Drought Index Package (version 2). Tarbiat Modares University, Tehran, Iran.
Mostafazadeh, R., Zabihi, M., 2016. Comparison of SPI and SPEI indices to meteorological drought assessment using R programming (case study: Kurdistan Province). J. Earth Space Phys. 42 (3), 633–643.
Mourato, S., Moreira, M., Corte-Real, J., 2010. Interannual variability of precipitation distribution patterns in Southern Portugal. Int. J. Climatol. 30, 1784–1794.
Murphy, S.J., Washington, R., 2001. United Kingdom and Ireland precipitation variations and the North Atlantic sea-level pressure field. Int. J. Climatol. 21 (8), 939–959.
Murphy, C., Harrigan, S., Hall, J., Wilby, R.L., 2013. Climate-driven trends in mean and high flows from a network of reference stations in Ireland. Hydrol. Sci. J. 58 (4), 755772.
Naeem, S., 1998. Species redundancy and ecosystem reliability. Conserv. Biol. 12 (1), 39–45.
Nunes, J.P., Jacinto, R., Keizer, J.J., 2017. Combined impacts of climate and socio-economic scenarios on irrigation water availability for a dry Mediterranean reservoir. Sci. Total Environ. 584–585C, 219–233.
OSI, Ordnance Survey Ireland, 2010. Water matters: our plan, north western international river basin management plan (2009–2015). Incorporating Amendments of the Minister for the Environment, Heritage and Local Government Issued on 6th July 2010. 124 p.
Owrangi, M.A., Adamowski, J., Rahnemaei, M., Mohammadzadeh, A., Afshin Sharifan, R., 2011. Drought monitoring methodology based on AVHRR images and SPOT vegetation maps. J. Water Resour. Prot. 3, 325–334.
Paredes, D., Trigo, R.M., García-Herrera, R., Trigo, I.F., 2006. Understanding precipitation changes in Iberia in early spring: weather typing and storm-tracking approaches. J. Hydrometeorol. 7, 101–113.
Ramos, C., Reis, E., 2002. Floods in Southern Portugal: their physical and human causes,

impacts and human response. Mitigation Adapt. Strateg. Glob. Change 7 (3), 267–284.
Sadeghi, S.H.R., Hazbavi, Z., 2015. Trend analysis of the rainfall erosivity index at different time scales in Iran. Nat. Hazards 77, 383–404.
Sadeghi, S.H.R., Hazbavi, Z., 2017. Spatiotemporal variation of watershed health propensity through reliability-resilience-vulnerability based drought index (case study: Shazand Watershed in Iran). Sci. Total Environ. 587–588, 168–176.
Sadeghi, S.H.R., Hazbavi, Z., Younesi, H., 2014. Sustainable watershed management through applying appropriate level of soil amendments. In: Sustainable Watershed Management – Proceedings of the 2nd International Conference on Sustainable Watershed Management, SUWAMA 2014, 13–15 October 2014. Sarigerme, Turkey. pp. 183–185.
Sadeghi, S.H.R., Hazbavi, Z., Kiani Harchegani, M., 2016a. Controllability of runoff and soil loss from small plots treated by vinasse-produced biochar. Sci. Total Environ. 541, 483–490.
Sadeghi, S.H.R., Hazbavi, Z., Younesi, H., Bahramifar, N., 2016b. Trade-off between runoff and sediments from treated erosion plots and polyacrylamide and acrylamide residues. Catena 142, 213–220.
Santo, F.E., Ramos, A.M., de Lima, M.I.P., Trigo, R.M., 2014. Seasonal changes in daily precipitation extremes in mainland Portugal from 1941 to 2007. Reg. Environ. Change 14, 1765–1788.
Shahabfar, A., Eitzinger, J., 2013. Spatio-temporal analysis of droughts in semi-arid regions by using meteorological drought indices. Atmosphere 4, 94–112.
Sood, A., Ritter, W.F., 2011. Developing a framework to measure watershed sustainability by using hydrological/water quality model. J. Water Resour. Prot. 3, 788–804.
Sternberg, M., Holzapfel, C., Tielbörger, K., Sarah, P., Kigel, J., Lavee, H., Fleischer, A., Jeltsch, F., Köchy, M., 2011. The use and misuse of climatic gradients for evaluating climate impact on dryland ecosystems- an example for the solution of conceptual problems. Climate Change-Geophysical Foundations and Ecological Effects, 11th Edition. InTech, pp. 362–374 Chapter 18.
Teegavarapu, R.S.V., 2017. Climate variability and changes in precipitation extremes and characteristics. In: Kolokytha, E., Oishi, S., Teegavarapu, R.S.V. (Eds.), Sustainable Water Resources Planning and Management Under Climate Change. Springer, Singapore, pp. 3–37 Chapter 1 ISBN 978–981-10-2049-0.
Trigo, R.M., DaCamara, C., 2000. Circulation weather types and their impact on the precipitation regime in Portugal. Int. J. Climatol. 20, 1559–1581.
van Dijk, A.I.J.M., Beck, H.E., Crosbie, R.S., de Jeu, R.A.M., Liu, Y.Y., Podger, G.M., Timbal, B., Viney, N.R., 2013. The millennium drought in southeast Australia (2001–2009): natural and human causes and implications for water resources, ecosystems, economy, and society. Water Resour. Res. 49 (2), 1040–1057.
Wiegand, A.N., Walker, C., Duncan, P.F., Roiko, A., Tindale, N., 2013. A systematic approach for modelling quantitative lake ecosystem data to facilitate proactive urban lake management. Environ. Syst. Res. 2, 12.
Yu, G., Yu, Q., Hu, L., Zhang, S., Fu, T., Zhou, X., He, X., Liu, Y., Wang, S., Jia, H., 2013. Ecosystem health assessment based on analysis of a land use database. Appl. Geogr. 44, 154–164.
Zareian, M.J., Eslamian, S., Gohari, A., Adamowski, J.F., 2017. The Effect of Climate Change on Watershed Water Balance: Mathematical Advances Towards Sustainable Environmental Systems. Springer International Publishing, pp. 215–238.